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PROSPECTS FOR INVESTIGATING UNUSUAL NUCLEAR REACTION ENVIRONMENTS USING THE NATIONAL IGNITION FACILITY[#]

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The standard capsule design[1] and other laser plasma targets at the National Ignition Facility offer the possibility of generating and studying thermal rates for significant astrophysical fusion reactions such as $^{3}He(^{3}He,2p)\alpha$, $^{7}Be(p,\gamma)^{8}B$, *and* $^{15}N(p,\alpha)^{12}C$. *At present the "S" factors for these reactions are determined either by extrapolation from higher energy scattering data[2,3] or by underground laboratory, low event rate experiments such as at LUNA[2,3] on un-ionized atoms with concomitantly large screening corrections. The ability to directly generate astrophysical fusion reactions in thermonuclear plasmas will be complemented by new, ab initio, "no frozen core" detailed shell model predictions for such light ion reactions.[4] In addition, the expected fluence of neutrons from the main* $D + T \rightarrow \alpha + n$ *burn reaction, is high enough to drive 10-20% of seeded spectator nuclei into excited states via (n,n') reactions. Furthermore, the ~2% 'minority'* $D + D \rightarrow {}^{3}He + n$ *and* $n + D \rightarrow n' + D'$ *scattering can drive reactions pertinent to the r, s, and p process nucleosynthesis of heavy elements,[5] including branches that pass through excited states with t > 10 ps, that can be studied using particle spectroscopy and radiochemistry[6] Additionally, for the first time, it will be possible to measure the effects of plasma screening on thermonuclear reactions. In the latter arena it will be possible to address the extent of quantum corrections to Salpeter screening.[7] Radiochemistry measurements of noble gas end species can be made with very high efficiency with only ~* 10^{4-5} *atoms required. Solid collection systems are being developed as well (with* $>10^{8}$ *atoms required at present). Because the capsule is essentially thin to neutrons, the reaction rate on an advected set of marker nuclei is a linear functional of the neutron source distribution. Determining this source function is thus computationally analogous to similar problems in medical imaging.[8]*

INTRODUCTION

The potential of the National Ignition Facility for creating and probing high energy density plasmas has been the subject of serious analysis for some time. However, while inertial fusion proper has long been a key goal of the NIF program, the general study and exploitation of nuclear reactions generated in inertial fusion capsules has just begun.[9] In fact, the unique conditions associated with ignition at NIF offer the prospect of being able to study significant, previously difficult to measure or calculate astrophysical reactions. In addition, related nuclear reactions, used to produce radiochemical diagnostic products can help determine characteristics of the burning plasma.

The unique conditions associated with burning inertial fusion capsules fall into the categories of thermonuclear fusion per se and high neutron flux and are as follows: successful runaway burn in NIF capsules produces widely differing ion and electron temperatures greatly exceeding the 1 keV equilibrium temperature at the center of the sun thus exhibiting weaker plasma screening conditions; the main D + T $\rightarrow \alpha + n$ burn reaction produces about 10^{19} neutrons within about 200 keV of 14 Mev in 20 ps. Because this time scale is short compared with a typical excited state nuclear gamma decay lifetime, it is appropriate to focus on the neutron fluence of about 1-2 10^{23} neutrons/cm^2 at the ablator surface. Thus, for typical neutron driven partial cross sections of about a barn (10^{-24} cm^2), 10-20% of seeded spectator nuclei will be driven into excited states capable of participating in multiple step reactions.

Because the extraction of basic nuclear physics information will be difficult, we advocate initially exploiting known or computed nuclear data for capsule diagnostic purposes. Eventually, well-characterized implosions will be applied to probe nuclear physics.

ASTROPHYSICAL APPLICATIONS OF FUSION CONDITIONS

Thermonuclear reaction rates between species i and j are of the form

$$R \sim \sigma_{ij} v_f \qquad \sigma_{ij} = \frac{S_{ij}(\varepsilon_p)}{\varepsilon_p} e^{-\pi(\varepsilon_G/\varepsilon_p)^{1/2}}$$

where ε_G is the relevant "Gamow energy," ε_p is the projectile energy, $S_{ij}(\varepsilon)$ is the S factor and f(p) denotes the plasma thermal average weighting function (e.g. Maxwell-Boltzmann or Fermi-Dirac). S factors are typically extrapolated to very low event rate stellar conditions from much higher energy data importantly including assumptions about the presence or absence of Breit-Wigner resonances.[2,3] These extrapolations also include large 'cold' electron screening effects. Present ab initio calculations of key rates, such as $^{3}He(^{3}He,2p)\alpha$ are only accurate to ~50%, motivating new experiments and calculations. Figure 1 displays S factor extrapolations for this rate, including results from the LUNA experiment.[3]

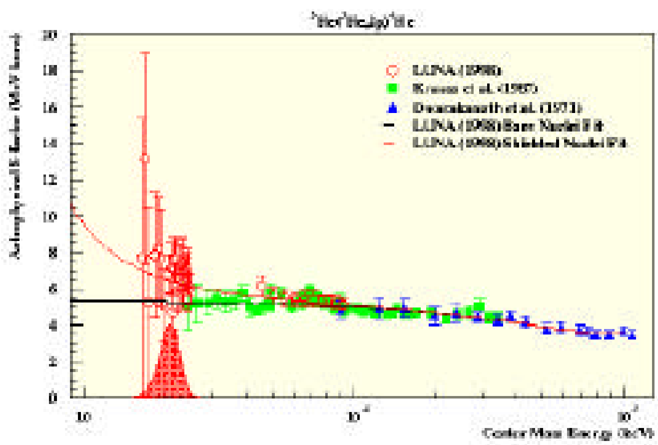

Figure 1 – Experimental S(E) variation for $^{3}He(^{3}He,2p)\alpha$ including cold atomic screening.[2,3] Note a possible Breit-Wigner resonance in the neighborhood of the Gamow peak for a 1 keV solar plasma.

Under solar conditions at 1 keV, the pp-I cycle, beginning with protons and ultimately producing ^{4}He via $^{3}He(^{3}He,2p)\alpha$ is the main energy producing pathway. The standard solar model integral prediction[10] for the ^{8}B neutrino deficit relies on both the $^{3}He(^{3}He,2p)\alpha$ and $^{3}He(^{4}He,\gamma)^{7}Be$ rates (the pp-II and pp-III precursors) and has been verified to about 10-20% by observation of transmuted neutrino species.[11] Accurate measurements and computations[4] of these rates under near solar conditions would further the determination of neutrino masses and mixing angles as well as other astrophysical structure investigations such as helioseismology.[12]

As one of a sequence of cases proposed to explore a range of ion temperatures, a capsule with 10^{17} ^{3}He atoms (due to T decay) brought to 8 keV at 100 gr/cc produces approximately 10^{8} $^{3}He(^{3}He,2p)\alpha$ reactions, possibly measurable through proton spectroscopy.[9] Likewise, $^{3}He(^{4}He,\gamma)^{7}Be$ might be measured by a combination of gamma spectroscopy and Be radiochemistry. Finally, key CNO cycle reactions such as $^{15}N(p,\alpha)^{12}C$ may be measured. In each of the cases, as has already been noted in Omega nuclear spectroscopy experiments,[9] one must devise ways to distinguish between the desired thermal rates characterized by a well-defined ion temperature, and parasitic in-flight reactions.

Finally, plasma screening, though a modest correction compared to the large screening effects already noted for E≤ 40 keV in cold, light atoms, remains an important practical and intellectual question. Long ago, Salpeter pointed out that classical Debye screening of the Gamow barrier enhances the pp and $p(^{7}Be,\gamma)^{8}B$ reactions by 5 and 20% respectively.[2,7]

$$\Gamma_{Salpeter} = \Gamma_0 \exp(e_1 e_2 \kappa_D \beta)$$
$$\kappa_D^2 = \sum 4\pi (Z_s e)^2 \beta \; n_{s\ \beta}$$

Here, e_1 and e_2 are the charges of the fusing ions, κ_D is the Debye wavevector and n_s and Z_s respectively are the density and charge of the plasma species s. The question remains of the size of 'off momentum shell' effects causing significant quantum corrections to the Maxwell-Boltzmann (or Fermi-Dirac) form of the weighting function f(p) for either the 1 keV solar case or for denser, cooler stars.[7] Brown and Sawyer's equilibrium prediction goes like $\kappa_D \lambda_e$ (where λ_e is the electron thermal wavelength) and is small:

$$\Delta\Gamma \sim -\Gamma_0(\beta e_1 e_2 \kappa_D^2 \lambda_e)/8$$

In contrast, non-equilibrium arguments suggest large modifications via effective changes in f(p) that also depend on the ion mass through the ion-plasma collision frequency ν_p thereby causing larger corrections to R:

$$f(p) = f_{MB} + \frac{h\nu_p}{2\pi\varepsilon_p^2} e^{\frac{\mu}{T}}$$

In capsules, multi-temperature, non-equilibrium effects will further complicate this question.

HIGH NEUTRON FLUENCES, R P AND S PROCESS, EXCITED STATE AND DIAGNOSTIC REACTIONS

Figure 2 shows the predicted neutron spectra from three generic DT implosions displaying behaviors from ignition to low yield. As noted above, while the capsule is 'thin' to neutrons up to ~ 10%, these 10% corrections can drive minority, but measurable multiple step reactions. The spectrum is dominated by the hard component around 14 MeV due to the reaction D + T

$\rightarrow$ α + n that has no analog in astrophysical nucleosynthesis. However, for example there is also a useful, softer component ≤ 2 MeV due to D + D$\rightarrow$ ^{3}He + n, as well as neutron elastic scattering. The relative strength of these spectral components is a complex function of the imploded capsule ρR and ion temperature.

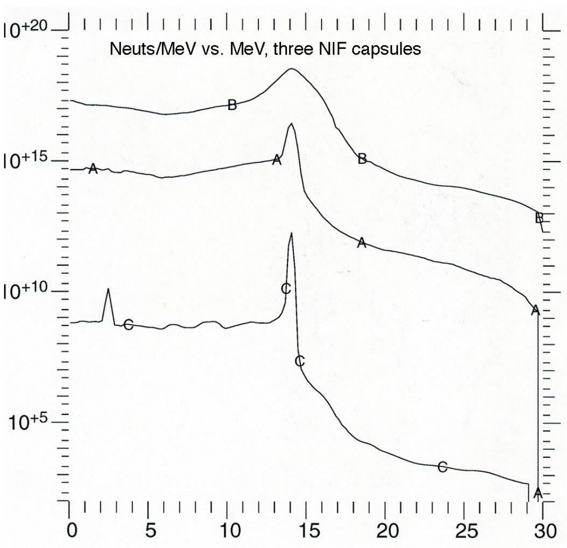

Figure 2 - Calculated neutron spectra for three capsules: A - 2D fizzle Y(yield) ~ 59 kilojoules, B - clean 1D ignition Y~20MJ, C – low yield 1D, no pulse shape, low drive, Y~1 joule. Scattering of DT neutrons, DD, TT, and in-flight secondary/tertiary reactions populate spectral bins away from 14 MeV.

Nucleosynthesis of the elements beyond iron is dominated by series of (n,γ) reactions driven by neutrons of E<1-2 MeV that fall into the categories of "r (rapid) and s (slow) process" depending on whether or not the flux of neutrons drives reactions faster than the pertinent product beta lifetime. While the relative importance of s and r process for most isotopes is known, the issue of their astrophysical site(s) and variety of mechanisms (particularly for r process variants) remains open.[5] Figure 3 shows the nucleosynthesis pathways for mid-Z elements, illustrating the importance of competing paths. Unlike the low Z, charged particle, few body reactions discussed above, computing these neutron reactions requires a statistical (Hauser-Feshbach) approach.[3] For the hard neutron reactions expected at NIF, the aggregate uncertainty for the total cross section for all relevant channels such as (n,2n) at a given energy is surprisingly only about 5-10%. This is because it is controlled by unitarity and the fact that above threshold, a few reactions of the (n,xn) type dominate because of their large phase space. However, the needed information on lower energy branching ratios is less well known. Experiments with radiochemical tracers at dopant levels low enough to leave D+T ignition unperturbed would thus be an important way to disentangle these networks.

It should also be remarked that these experiments taking advantage of observing reactions on the large excited state fraction of the marker nuclei (with lifetimes as short as 10 ps) are complementary to those proposed at a rare isotope accelerator intended to study reactions on much longer lived species (true isomers and beta unstable ground states).[13]

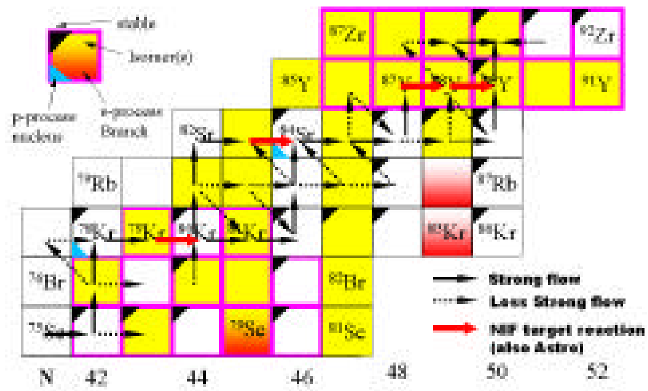

Figure 3 – Neutron driven nucleosynthesis networks for isotopes with Z ranging from 34 to 40, including αr, s, process branches, p nuclei, important isomeric intermediate states,[5] and possible practical NIF tracer overlaps.

Focusing on the example of Yttrium (Z=39) (n,2n) and (n,γ) reaction network in figure 4, one sees typical pathways controlled by the hard capsule spectrum.

At ^{89}Y capsule (e.g. inner ablator) dopant levels of 10^{15}, the basic 'minority' (n,γ) reaction, given the computed capsule flux for neutrons with E≤ 2 MeV and σ ~ 100 millibarns, produces 10^{11} ^{90}Y atoms, with various branches still measurable, though reduced proportionately.

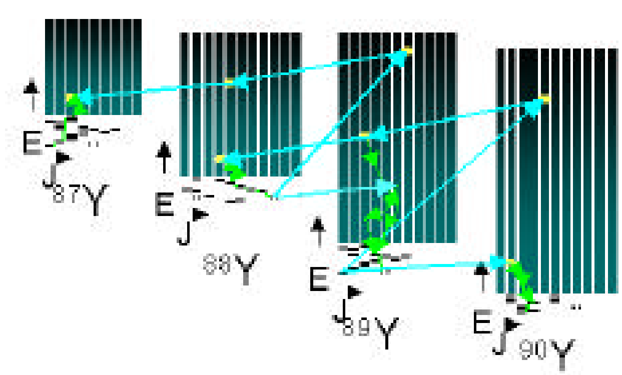

Figure 4 –Yttrium (Z=39) reaction network shows the role of low lying discrete states as well as the higher quasi-statistical continua. Both (n,2n) and (n,γ) are shown.

It is important to emphasize that, unlike the aforementioned charged particle case, the rates (which we have already noted to be well bounded) for the main (n,2n) neutron driven reactions are essentially a linear function of the spectator nucleus position. While disentangling the complex networks involves sifting through the minority reaction branches, the main reaction only depends on the neutron source function from the local $D + T \rightarrow \alpha + n$ distribution. Therefore, the neutron reactions on multiple advected target nuclei can give tomographic information on the rate of capsule burn using algorithms similar to medical imaging.[8]

RADIOCHEMISTRY AND GAS SAMPLING

One may contemplate two complementary measurement schemes: product spectroscopy and radiochemistry. The former has already been successfully applied as a diagnostic at the Omega laser.[9] Here we turn to radiochemistry. For noble gas end species such as He, Ne, Ar, Kr, and Xe, gas sampling from the pumping the target chamber in principle has very high efficiency. Figure 5 shows a schematic of the gas sampling/recovery system soon to be tested at the Omega laser.[6] The minimum detectable amount (MDA) required to make a 1% accurate measurement of, for example, ^{21}Ne, is approximately 10000 atoms. This considers factors such as the analysis efficiency of the mass spectrometer, background levels of ^{21}Ne in both the mass spectrometer, and in the gas-handling manifolds (both at the collection site on the target chamber and at the analysis laboratory), and background levels of ^{21}Ne in the target chamber. If the ^{21}Ne chamber background is higher than estimated, concomitantly more ^{21}Ne reaction product would be required to improve the signal-to-background. Since the current gas sampling collection scheme has a collection efficiency of about 45% (merely the ratio of sample bottle volumes to manifold volume), one would really need to produce about 22250 atoms of ^{21}Ne in order to exceed the MDA. In addition, the uncertainty in measurement is somewhat larger for sample amounts near the MDA. Therefore, to obtain an uncertainty of 1% or less on the measured ^{21}Ne, more than 22250 atoms would need to be produced in the reaction. A comfortable sample size would be 1 million ^{21}Ne atoms. **It should be clear that the MDA and the amounts required for measurement uncertainties of 1% or less are mostly independent and are strongly dependent on the isotope to be analyzed and the analysis method used.** For example, since ^{38}Ar backgrounds are higher, the MDA is nearer to 10^7 atoms. Even ^{37}Ar, analyzed using gas proportional counting rather than noble gas mass spectrometry because of increased sensitivity, requires a different MDA. Also, for unstable isotopes, the time required for any sample preparation or retrieval impacts the measurement differently depending upon the half-life of the analyte.

Even accounting for these caveats, the noble gas product production estimates meet the MDA requirements for most of the reactions considered. The present situation with solid recovery is quite different, with the subtended solid angle of detection surfaces ($\sim 10^{-4}$) being a major handicap in addition to chemical and detector efficiencies, half life losses, count lengths and so on. . For these cases, even simplistically arguing for efficiencies going like the subtended detector angle times statistical counting, recovery of ~ 10^8 atoms is required to produce the same accuracy. Though adequate for some of the neutron driven reactions, this situation clearly invites innovation!

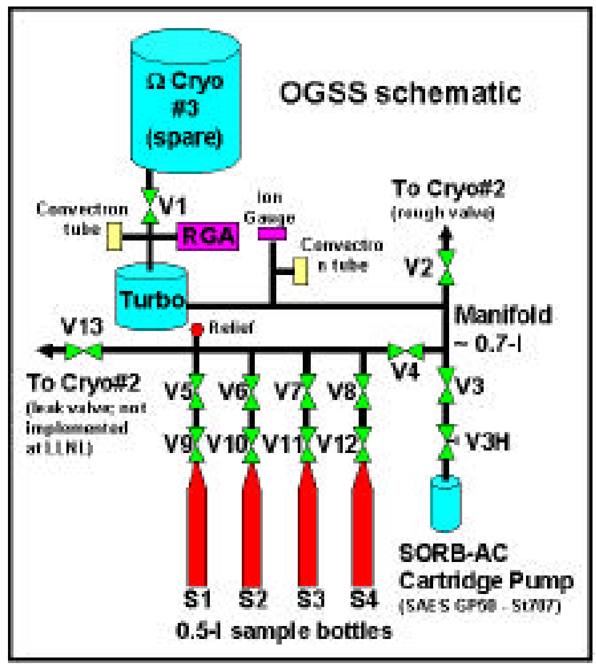

Figure 5 – Schematic of the Omega Gas Sampling System.[6]

CONCLUSIONS

In summary, we have proposed two broad classes of nuclear physics experiments at the National Ignition Facility. Both utilize ignition/implosion capsules. The first is pertinent to the standard solar model and CNO cycle stars as well as to the validation of new ab initio few body shell model calculations. These are low Z charged particle fusion reaction experiments with the goal of pinning down their ‘astrophysical’ S(E) factors to high accuracy. With the specific (indirect) application to neutrino physics, to complement the LUNA experiments on ^{3}He(^{3}He,2p)α as well as the neutrino mixing results from SNO, one desires rates with better than 10% accuracy – clearly a very tall order! For other applications, such as confirmation of CNO cycle rates, and the shell model calculations, the goal is to obtain rates with accuracies better than 50%.

The absence of large 'cold' atomic screening corrections constitutes an important advantage of measuring these rates directly in thermonuclear plasmas.

The second class of experiments would utilize the enormous neutron flux to produce multiple step spectator reactions relevant to r and s process nucleosynthesis. In this case, capsule experiments would be unique, though the task, using radiochemistry, of disentangling the complex reaction networks is daunting.

These experiments are complementary to the application of spectator reactions to the analysis of capsule burn. Because their integrated rate is (up to 10% corrections) a linear functional of the local rate of burn (neutron generation), the neutron reactions are a particularly promising diagnostic.

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13. The Rare Isotope Accelerator is a proposed to study relatively long-lived radioactive species reactions. Thus RIA will be complementary to regimes discussed here. See the ANL RIA website and the references therein at http://www.phy.anl.gov/ria